

# ROBOT VACUUM WITH EDGE AND OBJECT DETECTION SYSTEM

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# **ROBOTIC VACUUM CLEANER WITH EDGE AND OBJECT DETECTION SYSTEM**

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## **CLAIM OF PRIORITY**

[0001] This application claims priority to U.S. Patent Provisional Application No. 60/454,934 filed March 14, 2003; U.S. Provisional Application No. 60/518,756 filed November 10, 2003; U.S. Provisional Application No. 60/518,763 filed November 10, 2003; U.S. Provisional Application No. 60/526,868 filed December 4, 2003; U.S. Provisional Application No. 60/527,021 filed December 4, 2003 and U.S. Provisional Application No. 60/526,805 filed December 4, 2003. This application incorporates by reference U.S. Application Serial No. \_\_\_\_\_ entitled "Robot Vacuum" by Taylor et al., filed concurrently. (Attorney Docket No. SHPR-01360USS)

## **FIELD OF THE INVENTION**

[0002] The present invention relates to sensors, particularly to sensors for robots.

## **BACKGROUND**

[0003] A number of sensors have been developed for use on robots. Infrared (IR) or sonar sensors have been used on robots to detect wall or other objects. The information from the sensors can be used to map the environment of the robot. Mapping the environment of a robot using such sensors can be difficult. Often, information from different times or from multiple sensors is need to be combined in order to determine environmental features. Such relatively complex calculations can be difficult to do in real-time especially when other software processes needs to be executed on the robot.

[0004] It is desired to have a robot using an improved infrared sensors.

## **BRIEF SUMMARY**

**[0005]** One embodiment of the present invention is a robot including a motion unit; an infrared sensor and a processor. The infrared sensor includes an infrared light source to produce pulses of infrared light, optics to focus reflections from the infrared light pulse from different portions of the environment of the robot to different detectors in a 2D array of detectors. The detectors of the 2D array of detectors are adapted to produce an indication of the distance to the closest object in an associated portion of the environment. The processor receives the indications from the infrared sensor, determines a feature in the environment using the indications and controls the motion unit to avoid the feature.

**[0006]** An embodiment of the present invention is a method including producing pulses of infrared light, focusing reflections from the infrared light pulse from different portions of the environment of a robot to different detectors in a 2D array of detectors, the detectors producing an indication of the distance to the closest object in an associated portion of the environment, and using the indications from the infrared sensor to determine a feature in the environment so that the robot can be controlled to avoid the feature.

## **BRIEF DESCRIPTION OF THE DRAWINGS**

**[0007]** Figure 1 is a functional diagram of a robot including an infrared sensor of one embodiment of the present invention.

**[0008]** Figure 2 illustrates an example showing the operation of the infrared sensor of one embodiment of the present invention.

**[0009]** Figure 3 is a diagram that illustrates the use of reflected pulses for the example of Figure 2.

**[0010]** Figure 4 illustrates another embodiment of the operation of the infrared sensor for a robot.

**[0011]** Figure 5 illustrates the use of reflective pulses for the example of Figure 4.

**[0012]** Figure 6A - 6D illustrates the operation of the infrared sensor to detect features in the environment of a robot.

## DETAILED DESCRIPTION

[0013] Figure 1 illustrates one example of a Robot 100. In the example of Figure 1, the Robot 100 includes a motion unit 116. The motion unit 116 can be for example, wheels, tracks, legs or any element to control the operation of the robot 100. In one embodiment, the processor 118 uses motion control software 120 to control the motion unit 116. The motion unit 116 can include wheels, tracks, wings, legs or any other means of locomotion. The robot 100 also includes an IR sensor 102.

[0014] An infrared sensor 102 includes an infrared light source 104. The infrared light source 104 can produce pulses of infrared light. An infrared light sensor 102 includes optics 106 to focus reflections from an infrared light source pulse from different portions of the environment to different detectors in a two dimensional (2D) array of the detectors 108. The optics 106 can include a single or multiple optical elements. In one embodiment, the optics 106 focus light reflected from different regions of the environment to the detectors in the 2D array 108. The detectors produce indications of the distances to the closest objects in associated portions of the environment. In the example of Figure 1, the 2D array includes pixel detectors 110 and associated detector logic 112. In one embodiment, the 2D array of detectors is constructed of CMOS technology on a semiconductor substrate. The pixel detectors can be photodiodes. The detector logic 112 can include counters. In one embodiment, a counter for a pixel detector runs until a reflected pulse is received. The counter value thus indicates the time for the pulse to be sent from the IR sensor and reflected back from an object in the environment to the pixel detector. Different portions of environment with different objects will have different pulse transit times.

[0015] In one embodiment, each detector produces an indication of the distance to the closest object in the associated portion of the environment. Such indications can be sent from the 2D detector array 108 to a memory such as the Frame Buffer RAM 114 that stores frames of the indications. A frame can contain distance indication data of the pixel detectors for a single pulse.

[0016] Controller 105 can be used to initiate the operation of the IR pulse source 104 as well as to control the counters in the 2D detector array 108.

[0017] An exemplary infrared sensor for use in the present invention is available from Canesta, Inc. of San Jose, California. Details of such infrared sensors are described in the US

patent 6,323,932 and published patent applications US 2002/0140633 A1, US 2002/0063775 A1, US 2003/0076484 A1 each of which are incorporated herein by reference.

[0018] The processor 118 in one embodiment is adapted to receive the indications from the IR sensor 102. In one embodiment, the indications are stored in the frame buffer Random Access Memory (RAM) 114. The indications are used by the processor to determine a feature in the environment and to control the motion of the unit to avoid the feature. Examples of features include steps, walls and objects such as a chair legs. The advantage of the above described IR sensor with a two-dimensional array of detectors is that a full frame of distance indications can be created. Full frames of distance indications simplify feature detection. The burden on the processor 118 is also reduced. In one embodiment, feature detection software 122 receives frames of indications and uses the frames to detect features. Once the features are determined, the features can be added to an internal environment map with feature mapping software 124. The motion control software 120 can be used to track the position of the robot 100. Alternately, other elements can be used for positioning the robot. In one embodiment, the robot uses the indications from the detector to determine how to move the robot so that the robot avoids falling down stairs, and bumping into walls and other objects.

[0019] In one embodiment, the robot 100 is a robot cleaner that has an optional cleaning unit 126. Cleaning control software 128 can be used to control the operation of the cleaning unit 126.

[0020] In one embodiment, other sensors 130 are used. The other sensors 130 can include sonar sensors or simple infrared sensors positioned around the perimeter of the robot. The other sensors 130 can be used to improve the mapping or other operations of the robot 100.

[0021] One embodiment of the present invention is a robot, such a robot cleaner 100, that includes a sensor 102 producing multiple indications of distances to the closest object in an associated portion of the environment. A processor 118 receives indications from the sensor, determines a feature in the environment and controls a motion unit to avoid the feature. A determined feature can be indicated in an internal map. A determined feature can be indicated in an internal map. The determined feature can be a step, an object in a room, or other element.

[0022] Figure 2 illustrates the operation of a two-dimensional array of detectors. In the example of figure 2, a simplified one-dimensional slice of the two dimensional array is shown. In this example, regions 1, 2, 3, 4 and 5 extend over the edge of the step and thus do not receive

substantial reflections back to the two-dimensional array. Region 6 receives some reflections and steps 7 and 8 receive even more reflections.

[0023] Figure 3 illustrates an exemplary timing diagram for the reflections of the example of Figure 2. Reflections from objects located closer to the robot will return to the sensor sooner than reflections from objects that are further away. In one embodiment, the time from the start of the pulse to the start of the received reflection indicates the distance to an object.

[0024] Depending on the orientation of the objects, the detected reflections can be defuse or specular. Specular reflections are mirror-like reflections that result in high reflected intensities for a narrow angle range. Defuse reflections are relatively low intensities over a wider angle range. In the orientations of figure 3, floors and carpets tend to result in defuse reflections at the sensor while perpendicular objects such as walls tend to result in specular reflections at the sensor. The intensity of the reflected energy can be useful in obtaining information concerning the type of reflections. Reflective devices can be placed in the environment to increase the specular reflections at stair edges or other locations. In one example, the reflective devices can use retro reflective material such as a retro reflective tape or ribbon.

[0025] Alternately, the IR sensor can be oriented pointing down onto the floor at the edge of the robot. This results in greater specular reflections when the robot is over the floor. When the robot is over a descending stairway the reflections will be reduced. Based on this information the descending stairway can be detected. Using the IR sensor 102 with a 2D array 108 has the additional advantage that the orientation of the edge of the descending stairway can be determined. This can often give hints as to the orientation of a robot with respect to the room.

[0026] In one embodiment, the transmitted pulse is modulated. The modulated pulse can be used to detect low-energy defuse reflections.

[0027] In one embodiment, a cutoff time,  $t_{\text{cutoff}}$ , can be used. The total detected energy up to the cutoff time gives some indication of distance. The more reflected energy received up to the cutoff time, the closer the object is to the infrared sensor. Such an embodiment is especially useful for specular reflections.

[0028] Figure 4 illustrates an example, in which an object 404 is detected by the 2D array 400 and optics 402. The regions that detect the objects 404 regions 1, 2, 3, 4 and 5 will typically

have relatively strong reflections. Figure 5 illustrates an exemplary timing diagram for the reflections of the example of Figure 4.

[0029] Examples of the operation of an infrared detector of one embodiment are shown in Figures 6A to 6D. The example of 6A shows a simplified embodiment in which a 2D array produces a frame of indications of the distances to the closest objects in the environment. In the example of Figure 6A, an exemplary 4 x 4 frame of indications is used but the frame size and the number of regions examined can be much larger.

[0030] The regions are three dimensional but form a footprint on the floor shown by the dotted lines of Figure 6A. The example of Figure 6A illustrates the distance indications for a flat floor. Figure 6B illustrates a case in which an object **602** is in the detected region for the IR sensor. Figure 6C shows an example when the object **602** is closer to the robot. The changes of the distance indications can be used determine the size and location of the object. Walls can be detected due to their characteristic patterns.

[0031] Figure 6D illustrates an example of when the robot **600** approaches a step **604**. In this example, some regions indicate greatly increased distances or have no detected reflections due to the step. The robot **600** can thus determine the location of the step. Steps and objects can be avoided by the robot **600**. The position of the objects and steps can be stored in an internal map maintained by the robot **600**.

[0032] The foregoing description of preferred embodiments of the present invention has been provided for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many embodiments were chosen and described in order to best explain the principles of the invention and its practical application, thereby enabling others skilled in the art to understand the invention for various embodiments and with various modifications that are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims and their equivalence.